# Observed Non-Steady State Cooling and the Moderate Cluster Cooling Flow Model

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## ABSTRACT

We examine recent developments in the cluster cooling flow scenario following recent observations by *Chandra* and XMM-Newton. We show that the distribution of gas emissivity verses temperature determined by XMM-Newton gratings observations demonstrates that the central gas, i.e., where the cooling time is less than the age of the cluster, in cooling flow clusters cannot be in simple steady-state, i.e., $\dot{M}$ is not a constant at all temperatures. Based on the measured gas emissivity, the gas can only be in steady-state if there exists a steady heating mechanism that scales as $H(T) \propto T^{\alpha}$ where $\alpha = 1 - 2$. That is, a heating mechanism that preferentially targets the hottest and highest entropy gas, which seems very unlikely. Combining this result with the lack of spectroscopic evidence for gas below one-third of the ambient cluster temperature is strong evidence that the gas is heated intermittently. While the old steady-state isobaric cooling flow model is incompatible with recent observations, a "moderate cooling flow model", in which the gas undergoes intermittent heating that effectively reduces the age of a cooling flow is consistent with observations. Most of the gas within cooling flows resides in the hottest gas, which is prevented from cooling continuously and attaining a steady-state configuration. This results in a mass cooling rate that decreases with decreasing temperature, with a much lower mass cooling rate at the lowest temperatures. Such a temperature dependent $\dot{M}$ is required by the XMM-Newton RGS data and will produce an increasing amount of intermediate temperature gas which will then be reheated during the next heating cycle. We show the compatibility of this model for the cooling flow cluster A2052. The present paper strengthens the moderate cooling flow model, which can accommodate the unique activities observed in cooling flow clusters.

*Subject headings:* galaxies: clusters: general — cooling flows — intergalactic medium — X-rays: galaxies: clusters

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## 1. Introduction

Several recent papers have shown that the predictions of the steady-state cluster cooling flow (CF) model are inconsistent with *Chandra* and XMM-Newton X-ray observations (see review by Fabian 2003). Chandra observations show that the gas in the central regions of relaxed clusters with central dominant galaxies can be described as homogeneous single temperature gas with a positive temperature gradient. Ettori (2002) showed that the ASCA evidence for multiphase CFs was due to the poor spatial resolution of ASCA which could not distinguish between multiphase gas and single phase gas with a temperature gradient. Chandra observations show that only within the central few tens of kpc in clusters does the spectroscopy require additional components above a single temperature. Of course, this could simply be due to statistical and spatial resolution limitations in the Chandra data. The strongest evidence against the steady-state isobaric CF model is the lack of observered line emission in XMM-Newton RGS spectra from gas cooler than $\sim 1/3$ of ambient cluster temperatures (e.g., Kaastra et al. 2001; Peterson et al. 2001; Fabian 2003). In the so called "standard steady-state CF model", the age of a CF is assumed to be similar to the age of the cluster; namely the gas has been cooling for a long time. In the so called "moderate CF model" (Soker et al. 2001) heating is intermittent and the hot gas is not in steady-state, in the sense that its cooling time is longer than the time elapsed since the gas was last heated. Many reheating scenarios of the central gas in CFs have been proposed in the past with the aim of suppressing CFs altogether, or significantly reducing the average mass cooling rate (e.g., Binney & Tabor 1995; Tucker & David 1997; Ciotti & Ostriker 2001; David et al. 2001; Quilis, Bower, & Balogh 2001; Brüggen, M. & Kaiser 2001; Ruszkowski & Begelman 2002; Nulsen et al. 2002). These scenarios can be divided into models with steady heating by conduction or AGN, or non-steady, self-regulating models heated by nuclear outbursts. The moderate CF model is in the class of non-steady models where the gas cooling rate is peridocially heated by nuclear outbursts. We present below the evidence for non-steady CFs. The frequent occurrence of X-ray cavities coincident with radio lobes around the central dominant galaxy in CFs (e.g., Abell 496, Dupke & White 2002; Perseus [Abell 426], Fabian et al. 2002; Hydra A, McNamara et al. 2000) demonstrates that AGNs have a significant impact on the X-ray morphology of the hot gas. However, there are still significant uncertainties in the detailed physics of how the relativistic and thermal plasmas interact and how much heat is deposited into the hot gas.

In the moderate CF model where the intermittent heating is generated by AGN activity in the central dominant galaxy, it is expected that the amount of cooling gas increases sharply with increasing temperature. Only at very low temperatures is there a steady-state situation (i.e., where the cooling time is short compared to the time between nuclear outbursts). In Soker et al. (2001) we presented the arguments for a moderate CF in which the actual mass cooling rate is significantly below that derived under the assumption of the standard model, but a non-steady CF still exists. Soker et al. (2001) estimate that in the moderate cluster CF model the required kinetic energy of the AGN is $\sim 10^{47}$ erg s$^{-1}$, and its strong activity should last $\sim 10^{7}$ yr and occur every $\sim 10^{9}$ yr. Only $\sim 1\%$ of all CF clusters should be found during that stage. In Cygnus A there is a strong radio source which heats the intra cluster medium (Smith et al. 2002). Wilson, Young, & Smith (2003) estimate the mechanical power of the jets in Cygnus A to be $L_{\rm jet} \simeq 6 \times 10^{46}$ erg s$^{-1}$. This is $\sim 100$ times larger than the radio emission, and it is in the range required by the moderate CF model.

In recent analyses of XMM-Newton RGS data by Kahn et al. (2003) and Peterson et al. (2003; hereafter P2003) they find that there is less gas than that predicted by the steady-state isobaric CF model at all temperatures below the ambient gas temperature. Also, the discrepancy increases with decreasing temperature. There is not just a deficit in gas below $\sim 1/3$ of the ambient cluster temperature, there is a deficit of gas at all temperatures below the ambient temperature. They conclude that their results are difficult to reconcile with the newly proposed alternatives to the standard CF model, including those that completely suppress radiative cooling with some form of steady-state heating, and that new physics may be required. Our goal in this paper is to show that the XMM-Newton results are consistent with the expectations of the moderate CF model presented in Soker et al.(2001).

We convert the differential luminosity as a function of temperature as derived from the RGS data on cluster CFs into the distribution of gas mass verses temperature in §2. We also derive $\dot{M}$ as a function of temperature in this section and show that the gas in CFs cannot be in steady-sate. In section 3 we apply the moderate CF model to a recent Chandra observation of A2052, and in §4 we summarize our main results.

## 2. Distribution of Gas Mass with Temperature

We show in this and the next sections that the distribution of gas mass with temperature within cluster CFs found by P2003 can be incorporated into a model with intermittent heating, such that the effective age of the cooling gas is only $\sim 1 - 3 \times 10^{9}$ yr.

Based on RGS spectra of 14 CF clusters, P2003 find that the variation in the differential luminosity with gas temperature can be characterized by the following expression:

$$\frac{dL}{dT} = \frac{5}{2}\frac{\dot{M}_{\rm ocf} k}{\mu m_p}(\alpha+1)\left(\frac{T}{T_0}\right)^{\alpha}, \tag{1}$$

where $k$,$\mu$, and $m_p$ have their usual meaning, $\dot{M}_{\rm ocf}$ is the inferred mass cooling rate based on the assumptions inherent in the steady-state isobaric CF model, $T$ is the gas temperature, and $T_0$ is the maximum, or ambient cluster temperature. In general, the luminosity of gas cooling isobarically within a temperature interval $dT$ is:

$$dL = \frac{5}{2}\frac{k}{\mu m_p}\dot{M}(T)dT. \tag{2}$$

In steady-state, the rate gas cools into a given temperature interval must equal the rate gas cools out of the same temperature interval. In other words, $\dot{M}(T)$ must be a constant and equal to $\dot{M}_{ocf}$. Comparing equations (1) and (2) shows that the gas can only be in steady-state if $\alpha = 0$. Fitting the RGS data on their sample of 14 CF clusters, P2003 find that $\alpha \sim 1 - 2$. Within the old CF radius−where cooling time equals the cluster age−most of the radiation comes in the X-ray band. Only in the very inner region of $r \lesssim 10 - 30$ kpc a significant fraction of the energy lost by the cooling gas may be emitted in the optical and UV band (e.g., Fabian et al. 2002; Soker, Blanton & Sarazin 2003).

The mass cooling rate as a function of temperature can be written as:

$$\dot{M}(T) = \frac{dM}{dT}\frac{dT}{dt} = \frac{dM}{dT}\frac{T}{\tau_{\rm cool}}, \tag{3}$$

where we define the cooling time to be:

$$\tau_{\rm cool}(T) \equiv \frac{T}{dT/dt}. \tag{4}$$

¿From equations (2) and (3) we obtain

$$\frac{dL}{dT} = \frac{5}{2}\frac{k}{\mu m_p}\frac{dM}{dT}\frac{T}{\tau_{\rm cool}}. \tag{5}$$

Combining equations (1) and (5) gives:

$$\frac{dM}{dT} = \dot{M}_{\rm ocf}\tau_{\rm cool}(\alpha+1)\left(\frac{T}{T_0}\right)^{\alpha-1}\frac{1}{T_0}. \tag{6}$$

The cooling time varies as:

$$\tau_{\rm cool} = \tau_0\frac{\Lambda_0}{\Lambda}\frac{T}{T_0}\frac{n_0}{n} = \tau_0\frac{\Lambda_0}{\Lambda}\frac{P_0}{P}\left(\frac{T}{T_0}\right)^2, \tag{7}$$

where $\tau_0$ is the cooling time of gas at $T_0$, $n$ is the total number density, $P$ is the gas pressure, and $\Lambda$ is the radiative cooling function, such that $\Lambda n^2$ gives the energy radiated per unit volume per unit time. The last two equations can be combined to give:

$$\frac{dM}{dT} = \dot{M}_{\rm ocf}\tau_0(\alpha+1)\left(\frac{T}{T_0}\right)^{\alpha+1}\frac{1}{T_0}\frac{\Lambda_0}{\Lambda}\frac{P_0}{P}. \tag{8}$$

The cooling function can be characterized as:

$$\frac{\Lambda}{\Lambda_0} = \left(\frac{T}{T_0}\right)^{\eta} \tag{9}$$

where $\eta \simeq 1/2$ for $T \gtrsim 2 \times 10^7$ and $\eta \simeq -1/2$ at lower temperatures. For consistency with the expressions derived above, assuming isobaric cooling and integrating equation (8) over temperature gives:

$$M(<T) = \dot{M}_{\rm ocf}\tau_0 \frac{\alpha+1}{\alpha-\eta+2}\left(\frac{T}{T_0}\right)^{\alpha-\eta+2} \tag{10}$$

Setting $\alpha \simeq 1.5$ in the last equation, the average value found by P2003, and assuming Bremsstrahlung cooling ($\eta = 0.5$), gives:

$$M(<T) \simeq \dot{M}_{\rm ocf}\tau_0 \left(\frac{T}{T_0}\right)^{3}. \tag{11}$$

If we add a heating mechanism to equation (2), then a steady-state condition can be established only if $H(T) \propto T^{\alpha}$. It is difficult to conceive of a heating mechanism that preferentially heats the hottest and highest entropy gas in a CF. The RGS data show that $\dot{M}(T)$ increases with increasing temperature. If this were true over the lifetime of a cluster, there would be a large reservoir of gas at intermediate temperatures, which is also inconsistent with the RGS data. This gas must be periodically removed from these intermediate temperatures either by cooling sporadically to very low temperatures, which simply returns us to the classic CF problem, i.e., the lack of a significant reservoir of cool gas, or intermittent heating back to roughly the ambient temperature. We therefore examine the non-steady moderate CF model.

## 3. Moderate Cooling Flow Model

As an example, we consider the CF cluster A2052, which was included in the P2003 XMM-Newton sample, and whose X-ray structure as observed by Chandra was discussed in detail by Blanton et al. (2001, 2003). P2003 assume a cooling radius of $r_0 = 51$ arcsec, and find $\alpha \simeq 3$ for this cluster. Hence, from equation (10), $M(<T) \propto T^{4.5}$, and most of the mass is in the hottest gas.

Indeed, from fig. 4 of Blanton et al. (2003) we find that the mass within 30 arcsec consists of $\sim 30\%$ of the total gas mass within 50 arcsec. The temperature of the gas at 30 arcsec is 2.5 keV (Blanton et al. 2003). Using this along with an ambient temperature of $kT_0 = 3.3$ keV (Blanton et al. 2003), implies that $(2.5/3.3)^{4.5} = 29\%$ of the total gas mass up to $T_0$ resides at temperatures lower than 2.5 keV. Considering the uncertainties, these two numbers are in excellent agreement. A small fraction of the gas still resides at lower temperatures, presumably because the shock that heated the gas, say $\sim 10^9$ yrs ago, could not increase the cooling time of the lowest entropy gas above the time between outbursts (Soker et al. 2001).

P2003 did not compare their XMM-Newton results directly with Chandra data. We find the cooling time at 30 arcsec, with $kT = 2.5$ keV and $n_e = 0.02$ cm$^{-3}$ (Blanton et al. 2001), to be $\tau_{\rm cool}(30{\rm kpc}) = 1.5 \times 10^9$ yr. Interior to this radius the intracluster medium is disturbed by two large radio bubbles (Blanton et al. 2001). In the moderate CF model, the time interval between intermittent energy deposition is $1 - 4 \times 10^9$ yr, hence the gas is prohibited from settling into a steady-state configuration at $r > 30$ arcsec. Although the gas continues to cool and its cooling time gets shorter, it is unable to reach a steady-state before the next nuclear outburst.

Only within $r \sim 30$ arcsec may the gas have reached a steady-state, however the Chandra data show that it was recently disrupted by the two radio bubbles. We therefore expect that the actual cooling rate is much smaller than that in the old (standard) CF model. Based on a spectral analysis of the Chandra data, Blanton et al. (2003) find the mass cooling rate to be $26 < \dot{M} < 42 M_\odot$ yr$^{-1}$, which is $\sim 1/3$ of the old value within $r \sim 140$ arcsec (Perres et al. 1998). Taking the actual cooling radius to be the radius within which steady-state has been established based on the shorter age in the moderate CF model, the cooling rate will be even lower than the value found by Blanton et al (2003), i.e., we argue for a mass cooling rate of $\dot{M} \lesssim 10 M_\odot$ yr$^{-1}$.

Although we only study one cluster as an example, we note: (1) In the moderate CF model suggested by Soker et al. (2001), the heating doesn't inhibit the CF in the very inner region $r \lesssim 10$ kpc. In this region, the gas continues to cool to temperatures of $T \sim 10^4$ K, even after a heating event. Only in the outer regions does the heating event prevent the gas from cooling to low temperatures. Therefore, we don't expect the gas to be isothermal. The heating event can't heat the gas to extremely high temperature either, because this requires AGN energy output much larger than typical observed values. (2) The moderate CF model thus predicts that $\alpha$ in eq. (1), or $\alpha - \eta + 2$ in equation (10) will not take extreme values. We can't predict the exact range of values of $\alpha$ in the present study; this requires numerical simulations with variable conditions in the intracluster medium before each heating event, the energy supplied by the event, the time elapsed between events, and other processes, e.g., mergers. (3) Some CF clusters have central cooling times shorter than those in A2052. This does not pose a problem for the moderate CF model since the central regions of clusters still harbor a CF. (4) In light of the uncertainties, e.g., the temperature profile in the inner regions, the presence of X-ray cavities, and in the model parameters mentioned in point (2) above, it does not warrant a more extensive comparison with other clusters at this point. Future work, in particular numerical simulations of heating events, will include a greater comparison between the moderate CF theory and cluster observations.

## 4. Summary

We show that the differential luminosity of the gas in cluster cooling flows as a function of temperature, as derived from RGS XMM-Newton observations, is inconsistent with steady-state cooling flow scenarios, but is consistent with non-steady heating or moderate cooling flow models. The findings of P2003 imply that most of the gas in cooling flows resides in the highest temperature phase (eqs. 10 and 11 above). Within the context of the moderate cooling flow scenario (Soker et al. 2001), at these temperatures and densities the CF cannot reach a steady-state, and if the intermittent heating continues, it cannot attain such a state. Therefore, the rate of gas cooling at high temperatures is much higher than at lower temperatures.

We demonstrate the applicability of this model to the cooling flow cluster A2052 (Sec. 3). We argue for a mass cooling rate of $\lesssim 10 M_\odot$ yr$^{-1}$ in this cluster, which is compatible with the upper limit found by P2003 for lowest temperature gas. This is much lower than the cooling rate of hotter gas, $\gtrsim 100 M_\odot$ yr$^{-1}$, found by (P2003) or deduced in the old CF model by Peres et al. (1998), and somewhat lower than the cooling rate derived recently by Blanton et al. (2003) of $\sim 26 - 42 M_\odot$ yr$^{-1}$. Overall, intermittent heating in the moderate CF model (Soker 2001; Fabian 2003), or more frequent heating ( Blanton et al. 2003 for A2052), may account for the P2003 findings without invoking new processes. The intermittent heating model, with time intervals between major heating events of $\sim 1 - 3 \times 10^9$ yr has the advantage that no fine tuning is required to balance heating and cooling, since the gas is heated to relatively high temperatures, and then starts cooling. Most of the heated gas does not cool to low temperatures before the next major heating event. Different values of the physical parameters, e.g., energy input and time intervals between heating events, as well as a cluster's properties, will give different values of $\alpha$ in equations (1) and (10). Indeed, a large range of values is observed, $\alpha \sim 1 - 3$, hinting on a wide range in the physical parameters mentioned above, such that no fine tuning is observed or required. As shown in Soker et al. (2001), it is difficult to prevent the lowest entropy gas from complete cooling (i.e., increasing the cooling time above the time between heating events). Hence, a low $\dot{M}$ cooling flow can be sustained in the very central region of clusters.

This paper strengthens the moderate cooling flow model (Soker et al. 2001), by supporting the claim that the unique activities observed in cooling flow clusters (e.g., McNamara 2002 and references therein), can be accommodated within its framework. The problems which are need to be solved, e.g., the exact nature of the heating events, are less severe than the crisis encountered in the old cooling flow model.

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## REFERENCES

Binney, J., & Tabor, G. 1995, MNRAS, 276, 663

Blanton, E. L., Sarazin, C. L., & McNamara, B. R. 2003, ApJ, in press (astro-ph/0211027)

Blanton, E. L., Sarazin, C. L., McNamara, B. R., & Wise, M. W. 2001, ApJ, 558, L15

Brüggen, M., & Kaiser, C. R. 2001, Nature, 418, 301

Ciotti, L., & Ostriker J. P. 2001, ApJ, 551, 131

David, L. P., Nulsen, P. E. J., McNamara, B. R., Forman, W., Jones, C., Ponman, T., Robertson, B., & Wise, M. 2001, ApJ, 557, 546

Dupke, R., & White, R. E., III 2002, in ASP Conf. Ser. 262, High-Energy Universe at Sharp Focus: Chandra Science, ed. E. M. Schlegel & S. Vrtilek (San Francisco: ASP), 51

Ettori, S. 2002, MNRAS, 330, 971

Fabian, A. C. 2003, in Galaxy Evolution: Theory and Observations, eds. V. Avila-Reese, C. Firmani, C. Frenk, & C. Allen, RevMexAA SC, in press (astro-ph/ 0210150)

Fabian, A. C., Celotti, A., Blundell, K. M., Kassim, N. E., & Perley, R. A. 2002, MNRAS, 331, 369

Kaastra, J. S., Ferrigno, C., Tamura, T., Paerels, F. B. S., Peterson, J. R., & Mittaz, J. P. D 2001, A&A, 365, L99

Kahn, S. M., Peterson, J. R., Paerels, F. B. S., Xu, H., Kaastra, J. S., Ferrigno, C., Tamura, T., Bleeker, J. A. M., & Jernigan, J. G. 2003, (astro-ph/0210665)

McNamara, B. R. 2002, The High-Energy Universe at Sharp Focus: Chandra Science, Symposium at the ASP meeting, ASP Conference Proceedings, Vol. 262, eds. Eric M. Schlegel and Saeqa Dil Vrtilek, 351

McNamara, B. R., et al. 2000, ApJ, 534, L135

Nulsen, P.E.J., David, L., McNamara, B., Jones, C., Forman, W. , Wise, M. 2002, ApJ, 568, 163.

Peres, C. B., Fabian, A. C., Edge, A. C., Allen, S. W., Johnstone, R. M., White, D. A. 1998, MNRAS, 298, 416

Peterson, J. R., et al. 2001, A&A, 365, L104

Peterson, J. R., Kahn, S. M., Paerels, F. B. S., Kaastra, J. S., Tamura, T., Bleeker, J. A. M., Ferrigno, C., & Jernigan, J. G. 2003, ApJ, submitted (astro-ph/0210662) (P2003)

Quilis, V., Bower, R. G., & Balogh, M. L. 2001, MNRAS, 328, 1091

Ruszkowski, M., & Begelman, M. C. 2002, ApJ, 581, 223 (astro-ph/0207471)

Smith, D. A., Wilson, A. S., Arnaud, K. A., Terashima, Y., & Young, A. J. 2002, ApJ, 565, 195

Soker, N., White, R. E. III, David, L. P., & McNamara, B. R. 2001, ApJ, 549, 832

Tucker, W., & David, L. P. 1997, ApJ, 484, 602

Wilson, A. S., Young, A. J., & Smith, D. A. 2003, in Active Galactic Nuclei: from Central Engine to Hot Galaxies, ASP Conf. Ser., eds. S. Colin, F. Combes, and I. Shlosman in press (astro-ph/0211541)